Shallow-Water Propagation

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LONG-TERM GOALS

Develop methods for propagation and coherence calculations in complex shallow-water environments, determine their capabilities and accuracy, and apply them for modeling and understanding data.

OBJECTIVES

(A) Treat propagation from narrowband and broadband sources over elastic and poro-elastic sediments, and incorporate realistic bathymetric, topographic, and geoacoustic variations.

(B) Analyze and model data, quantify effects of random environmental and experimental variability, and efficiently determine field statistics for intensity and coherence.

APPROACH

(A) Develop high accuracy PE techniques for applications to shallow-water sediments, accounting for heterogeneities and anisotropy. Treat range dependence and layering by coordinate rotation and energy conservation methods. Benchmark results using independent procedures and data.

(B) Develop environmental representations for ocean and geoacoustic variability using data and parametric models. Perform acoustic field calculations with PE, normal mode, and perturbation methods. Use computational results and additional data to specify propagation mechanisms.

Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL) for model development; and Dr. William Carey (BU), Dr. James Lynch (WHOI), and their colleagues for analysis and simulation of experimental data.

WORK COMPLETED

(A) Our PE approach for layered elastic sediments, based on a formulation with new dependent variables and relying on a Galerkin procedure for handling interfaces accurately [1], is the foundation of recent progress for propagation through realistic sediments. Using this formulation

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in combination with a mapping technique [2], highly range-dependent environments including beaches, shelves, or sandbars, and conversions between waves such as Scholte to Rayleigh, can now be treated. A major generalization that employs coordinate rotations at slope changes of bathymetry provides very accurate solutions [3], even with relatively steep slopes, although the initial version is unsuitable where the bathymetric interface becomes topographic (as for a beach or an island). An extension is being completed [4] which provides this additional capability and shows improved accuracy over the mapping technique, which is exact only for constant slopes. To handle range-dependent interfaces in elastic sediments, another generalization of our formulation is required to account for energy conservation using the single scattering approximation [5]. A crucial step was achieved [6] by the development of an improved procedure to handle relatively large changes in sound speeds and interface slopes. Comparisons between high-quality laboratory tank measurements and calculations from our elastic model with coordinate rotations show that a remarkable level of agreement can be obtained [7]. Additional benchmarking examples are being carried out [8] to specify the performance of our techniques for other range-dependent propagation problems in elastic media. Improved estimates for sound speeds in transversely isotropic poro-elastic sediments permit quantification, using our PE model [9], of anisotropy effects on propagation. New examples show that calculations with a hybrid split-step PE method [10] are efficient as well as accurate at kilohertz frequencies.

(B) Comparisons between pulse data from one southwest track of the SWARM95 experiment and broadband propagation calculations [11] reveal that wavenumber spectrum resonance between acoustic modes and internal solitons produces the overall time behavior of integrated energy. This mechanism is robust, as demonstrated by calculations [12] in which the parameters specifying soliton characteristics and geoacoustic profiles are varied. In contrast, the measured time behavior from another southwest track arises from horizontal energy refraction between soliton wave front ducts [13], a mechanism previously discussed theoretically but never confirmed in data. An interference pattern analogous to the Lloyds Mirror is generated by propagation at low incident angles to wave fronts of nonlinear internal solitons, and these patterns persist in the presence of typical random variations in soliton properties [14]. Three-dimensional propagation calculations demonstrate [15] that mode coupling can arise from interactions of soliton wave fronts that occur in shallow water regions. Nonlinear frequency dependence of attenuation in the upper layers of sandy and silty sediments is shown [16], in new calculations using data from the ACT III experiment in the Strait of Korea, to be critical for modeling narrowband and broadband data and for useful estimates of transverse coherent length, Transverse coherent length determined from adiabatic mode calculations [17] varies strongly with horizontal direction when environmental correlation functions are anisotropi, as a result of processes such as internal solitons. Sediment attenuation frequency dependence plays a crucial role in a new examination of data from the ACT II experiment off New Jersey [18], in which a revised formulation produces nonlinear power exponents different from those obtained previously. This attenuation property must also be taken into account for broadband modeling and data comparisons at the New Jersey AGS site [19], where extensive environmental and acoustic observations are available. A simplified model of the mechanism by which this property produces typically observed values of modal attenuation coefficients has been constructed [20].

RESULTS (from two selected investigations)

(A) Shallow water propagation problems of interest require full capabilities for propagation over and through range-dependent elastic sediments. The two primary difficulties are accurate treatments of ocean-sediment/air-sediment boundary variations and of elastic-elastic interfaces in the sediment. Our recent progress [3], [4] resolved the first of these, and our approach automatically handles the second for cases where such interfaces follow the bathymetry. A more general capability is essential, since different sediment morphology can produce strong interface variations that dramatically affect propagation. The breakthrough required a combination of a single-scattering approach at vertical elastic-elastic interfaces [5] and a powerful iteration procedure [6] that assures convergence for interface slopes and elastic property changes which are as large as required for applications. Substantial changes in the stratigraphy of sediment heterogeneities present no difficulties for this procedure in determining the evolution of acoustic energy. One example is shown by the loss contours in **Figure 1,** for a four-layer elastic medium with interfacial range dependence so strong that one of the layers disappears at one range and returns at a longer range. Waveguide propagation is visible in two of the layers, along with energy exchanges among the upper layers. We conclude that our new method provides unparalleled capabilities for accurately handling elastic environments with significant range dependence.

(B) Internal solitons of large amplitude occur in many shallow water regions and affect acoustic variability substantially, so it is essential to quantify their influence for data analysis and performance predictions. For instance, it is known that acoustic propagation has striking features [23] in directions near those of soliton wave fronts, which are often nearly linear over several km or more. Soliton pulses typically appear in packets of several waves, and satellite data show packets arriving in multiple directions, often close to one another. An important question for predictability is whether efficient propagation calculations provide sufficient accuracy in the presence of interacting solitons; are calculations of standard 2-D type (allowing vertical mode coupling but not cross-range interactions) adequate, or are adiabatic 3-D (with horizontal refraction but not coupling of vertical modes) or fully 3-D (with both vertical and cross-range coupling of modes) necessary. Results from one example are displayed in **Figure 2**, for which two solitons propagate at slightly different angles as sketched at the lower right. The color panels show reduced transmission loss in the y = 0 plane from PE calculations with and without cross-range coupling. The modal patterns are generally similar, but beyond about 8 km the coupling case appears to show locations of much larger amplitude. This is confirmed by the cross-section curves at the lower left, where amplitude peaks for the two calculations differ by up to 6 dB. These differences result from mechanisms of cross-range mode coupling and refraction and do not change substantially if the single solitons are replaced by typical packets. We conclude from these and other calculations that soliton interactions produce significant intensity variations that can require 3-D propagation methods for accurate determination.

IMPACT/APPLICATIONS

New or improved capabilities for handling shallow-water sediment physical properties, including layering, anisotropy, elasticity, porosity, and dispersion, are made available for propagation predictions. Sediment interfacial variability, including range-dependent bathymetry and layer boundaries, can be handled accurately in calculations. Efficient determination of intensity and coherence statistics resulting from environmental fluctuations and experimental variability is feasible. Data analyses and comparisons allow specification, for experimental measurements and for

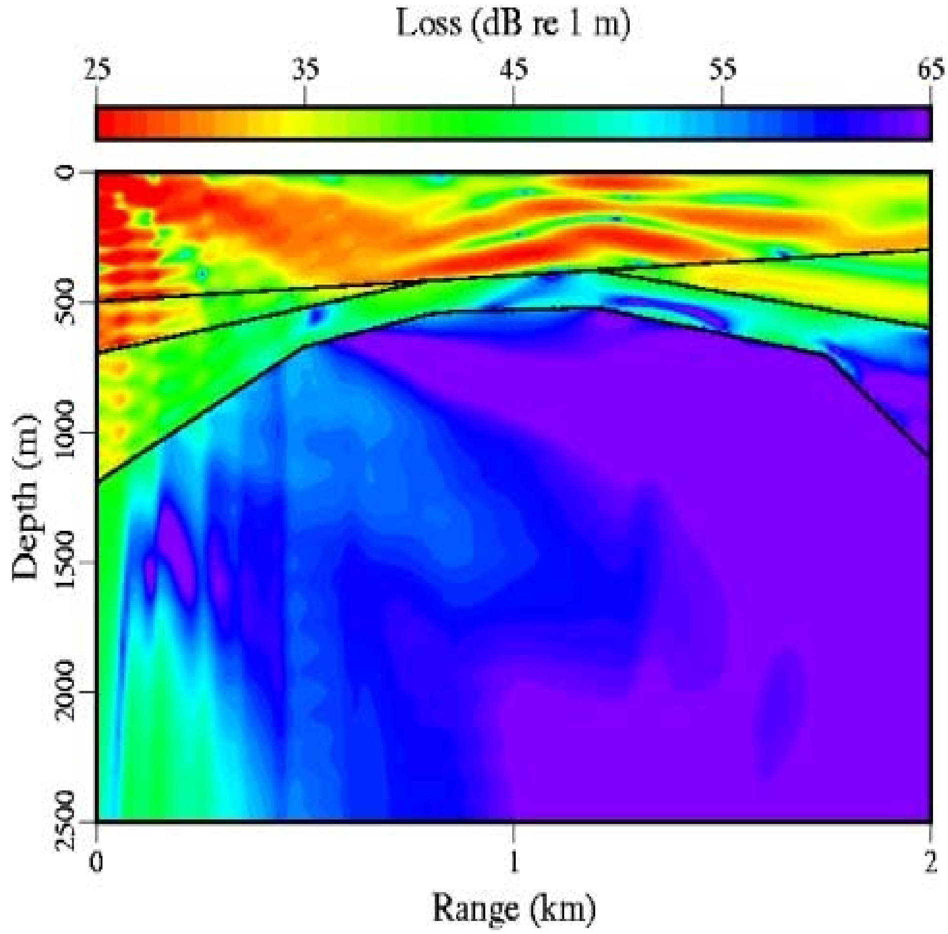
applications, of the relative significance of a variety of physical mechanisms; for examples, linear versus nonlinear frequency dependence of attenuation, water column versus bathymetric variability, and vertical versus horizontal coupling due to internal solitons and bathymetry. Results from modeling and data analyses of several experiments, including HCE, ACT, SWARM, are partly aimed toward improving shallow-water sonar systems and predictions. New propagation model implementations, data representation techniques, and analysis tools are being distributed to university and laboratory research groups.

RELATED PROJECTS

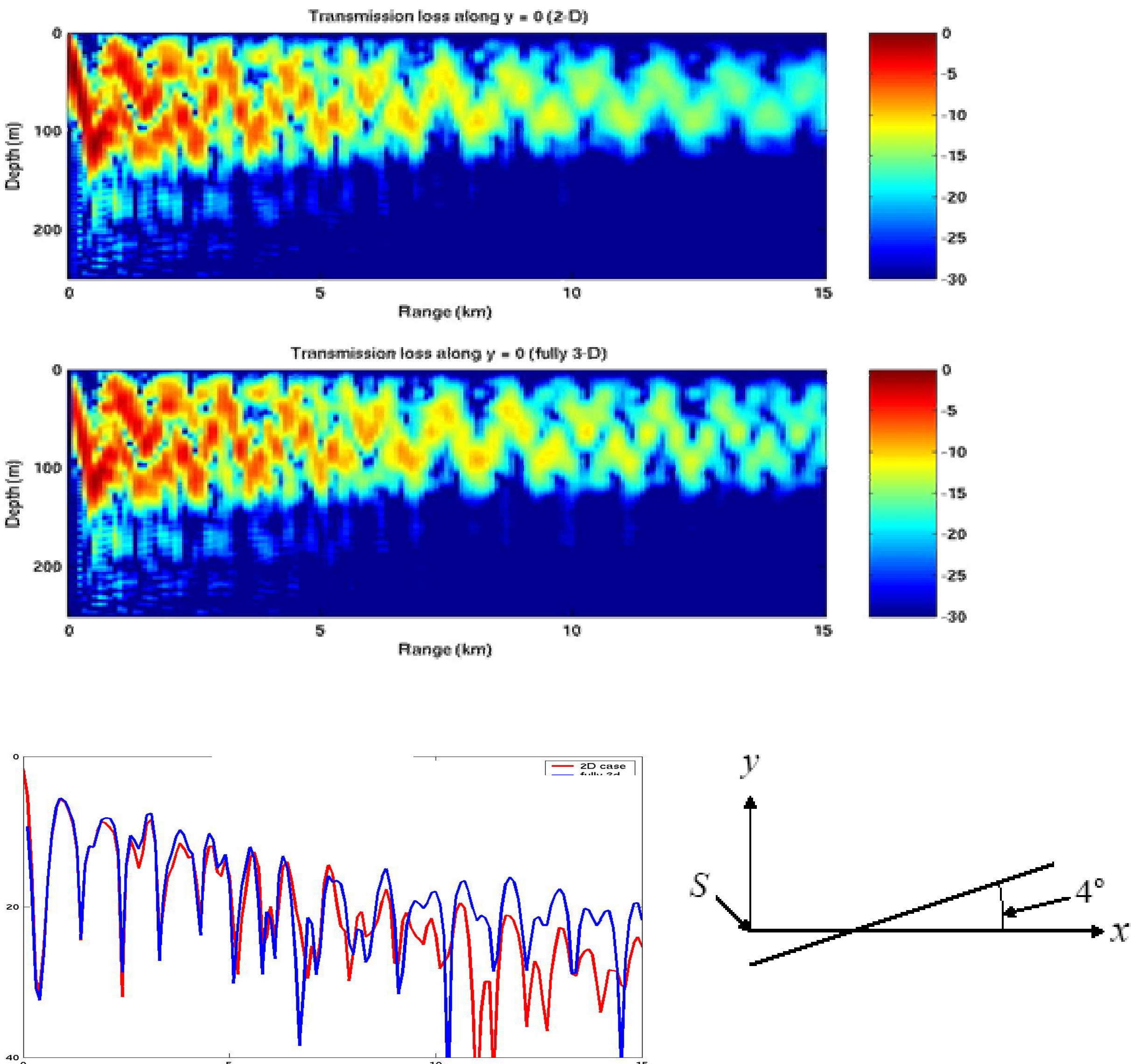
- Additional work with Dr. Michael Collins includes completion of a research monograph on state of the art PE models and applications [21], since the research technical issues have now been resolved. Applications of a new PE solution [22] illustrate effects of buoyancy and advection of waves in a fluid.

- Other research with Dr. James Lynch and his colleagues focuses on acoustic influences of azimuthal variability in shallow water. Propagating internal solitons generate such variability and lead to several interesting consequences [23], the most familiar being upper-ocean horizontal refraction [24]. Heterogeneous sediments with complex stratigraphy also have this capability [25].

- Ongoing work with Dr. William Carey and his colleagues examines predictability of narrowband propagation characteristics, including coherence scales and frequency dependence of sediment attenuation. Emphasis is on analysis of recent high-quality data sets and on understanding mechanisms responsible for the dominant features.



<u>Figure 1</u>. Seismo-acoustic propagation in layered elastic sediments, including substantial range dependence in layer interfaces, is treated efficiently and accurately by a new PE approach that uses single scattering at vertical interfaces. Transmission loss contours on a 25-65 dB scale, to 2500 m depth and 2 km range for a 10 Hz source at 100 m, are shown for a range-dependent layered environment. The first elastic layer decreases from 500 to 400 m over 2 km; the second, with maximum thickness of 300 m, appears as two wedge-shaped regions because it vanishes between 800 and 1200 m in range; the third has depth between 200 and 500 m and boundaries with up to five locations of slope changes; and the fourth is a thick basement. The four layers have compressional sound speeds of 1500, 1700, 2400, and 3400 m/s, shear speeds of 700, 800, 1200, and 1700 m/s, and densities of 1.0, 1.2, 1.5, and 2.5 g/cm^3. Compressional and shear attenuations in the upper layers are 0.1 and 0.2 dB/λ and are doubled in the basement. The calculation requires the extended procedure in Ref. [6], because the simpler method of Ref. [5] will not converge.
The contours show waveguide propagation in the top layer, coupling into and out of the second layer, ducted propagation in the third layer, and weak penetration into the basement.



<u>Figure 2</u>. Interactions of internal solitons can produce significant cross-range variations and modal coupling. <u>Lower right</u>: Schematic of propagation region in the horizontal xy-plane with acoustic source at the origin. One internal soliton (sech^2 pattern, maximum amplitude 10 m, width 270 m) propagates in the y-direction and is shown with its peak along the x-axis. A second soliton pulse propagates at an angle of 4 deg with the x-axis and intersects the first pulse 5 km from the source. <u>Upper panels</u>: Transmission loss contours with cylindrical spreading removed on a 0-30 dB scale are shown in the y = 0 plane, to 250 m depth and 15 km range for a 75 Hz source at 30 m. The sound speed profile has a thermocline to 40 m depth and is essentially isospeed to the 100 m water bottom. The top panel shows PE results with no cross-range diffractive (coupling) term, and the middle panel shows results including this term. Both pictures show modal waveguide propagation, and the levels appear substantially higher with coupling. <u>Lower left panel</u>: Sections of the color contours at a 20 m receiver versus range, on a 0-40 dB scale. As range increases beyond 8 km, the cross-range coupling curve (blue) has peak-amplitude differences up to 6 dB higher than the curve without coupling (red). The difference results from both horizontal refractionand cross-range modal coupling.

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